

# **Muon Collider Summary from TF**

**Fabio Maltoni**  
**Louvain U., CP3 and Bologna**

**Patrick Meade**  
**YITP Stony Brook**

# Plan

Where we've been...

Where we are, where we want to go, and why a muon collider is the coolest choice...

What is there to do?

# Plan

Where w

Where w

is the coo

What is t

on collider



# Plan

Where we've been...

Where we are, where we want to go, and why a muon collider is the coolest choice...

What is there to do?

**Where have we been as theorists in muon collider efforts?**

**Where have we been as theorists in muon collider efforts?**

**MISSING!**

find primarch hep-ph and t "muon collider" and date after 2013

[find j "Phys.Rev.Lett.,105\\*\\*" :: more](#)

## Muon Collider

Sort by:

Display results:

earliest date

desc.

- or rank by -

25 results

single list

[HEP](#)

12 records found

find primarch hep-ph and t "FCC" and date after 2013

[find j "Phys.Rev.Lett.,105\\*\\*" :: more](#)

## FCC

Sort by:

Display results:

earliest date

desc.

- or rank by -

25 results

single list

[HEP](#)

96 records found 1 - 25 ►► jump to record: 1

find primarch hep-ph and t "100 tev" and date after 2013

[find j "Phys.Rev.Lett.,105\\*\\*" :: more](#)

## 100 TeV

Sort by:

Display results:

earliest date

desc.

- or rank by -

25 results

single list

[HEP](#)

88 records found 1 - 25 ►► jump to record: 1

find primarch hep-ph and t "ILC" and date after 2013

[find j "Phys.Rev.Lett.,105\\*\\*" :: more](#)

## ILC

Sort by:

Display results:

earliest date

desc.

- or rank by -

25 results

single list

[HEP](#)

106 records found 1 - 25 ►► jump to record: 1

**Okay it's not *that* crazy**

Table 1  
Summary of Scenarios

	Scenarios		
	Scenario A	Scenario B	Scenario C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y
MAP	N	N	N

muon collider is persona non grata

A ridiculous tragedy like SSC or was it just ahead of its time?

Last P5

# Okay but what about the lead up to the last Snowmass/P5? Surely theorists were there?

find primarch hep-ph and t "muon collider" and date before 2013 and date after 2001

[find j "Phys.Rev.Lett.,105\\*" :: more](#)

Sort by:

earliest date

desc.

- or rank by -

Display results:

25 results

single list

[HEP](#)

17 records found

find primarch hep-ph and t "ILC" and date before 2013 and date after 2001

[find j "Phys.Rev.Lett.,105\\*" :: more](#)

Sort by:

earliest date

desc.

- or rank by -

Display results:

25 results

single list

[HEP](#)

207 records found 1 - 25 ►► jump to record:

# some...

# Okay but what about the lead up to the last Snowmass/P5? Surely theorists were there?

<input 2001"="" 2013="" after="" and="" before="" collider\"="" date="" muon="" type="text" value="find primarch hep-ph and t \"/>	<input 2001"="" 2013="" after="" and="" before="" date="" ilc\"="" type="text" value="find primarch hep-ph and t \"/>
<a href="#">find j \"Phys.Rev.Lett.,105*\" :: more</a>	<a href="#">find j \"Phys.Rev.Lett.,105*\" :: more</a>
Sort by: earliest date desc. - or rank by - 25 results single list	Sort by: earliest date desc. - or rank by - 25 results single list
<b>HEP</b> 17 records found	<b>HEP</b> 207 records found 1 - 25 ►► jump to record: 1

<input 100="" 2001"="" 2013="" after="" and="" before="" date="" tev\"="" type="text" value="find primarch hep-ph and t \"/>
<a href="#">find j \"Phys.Rev.Lett.,105*\" :: more</a>
Sort by: earliest date desc. - or rank by - 25 results single list
<b>HEP</b> 1 records found
1. Pure Gravity Mediation with $m_{3/2} = 10\text{--}100\text{ TeV}$

But 100 TeV wasn't even there yet and it dominated the landscape the last decade for pheno? This is physics not just sociology



# More recent physics efforts *just* since the pandemic...

## Measuring the quartic Higgs self-coupling at a multi-TeV muon collider

Mauro Chiesa (Annecy, LAPTH), Fabio Maltoni (Louvain U., CP3 and U. Bologna, DIFA and INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Barbara Mele (INFN, Rome), Fulvio Piccinini (INFN, Pavia) et al. (Mar 30 2020)

Published in: *JHEP* 09 (2020) 098 • e-Print: [2003.13628](#) [hep-ph]

## Vector boson fusion at multi-TeV muon colliders

Antonio Costantini (INFN, Bologna), Federico De Lillo (Louvain U., CP3), Fabio Maltoni (Louvain U., CP3 and Bologna U. an INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Olivier Mattelaer (Louvain U., CP3) et al. (May 20, 2020)

Published in: *JHEP* 09 (2020) 080 • e-Print: [2005.10289](#) [hep-ph]

## A Guaranteed Discovery at Future Muon Colliders


Rodolfo Capdevilla (Toronto U. and Perimeter Inst. Theor. Phys.), David Curtin (Toronto U.), Yonatan Kahn (Illinois U., Urbana), Gordan Krnjaic (Fermilab) (Jun 29, 2020)

e-Print: [2006.16277](#) [hep-ph]

## Probing the muon g-2 anomaly at a Muon Collider

Dario Buttazzo (INFN, Pisa), Paride Paradisi (Padua U. and INFN, Padua) (Dec 4, 2020)

e-Print: [2012.02769](#) [hep-ph]

 pdf  cite

## Gauged $L_\mu - L_\tau$ at a muon collider

Guo-yuan Huang, Farinaldo S. Queiroz, Werner Rodejohann (Jan 13, 2021)

e-Print: [2101.04956](#) [hep-ph]

 pdf  cite

[arXiv:2101.10469](#) [pdf, other]

## Probing electroweak phase transition with multi-TeV muon colliders and gravitational waves

Wei Liu, Ke-Pan Xie

Comments: 21 pages, 5 figures

Subjects: **High Energy Physics – Phenomenology (hep-ph)**

## High Energy Leptonic Collisions and Electroweak Parton Distribution Functions

Tao Han (Pittsburgh U.), Yang Ma (Pittsburgh U.), Keping Xie (Pittsburgh U.) (Jul 28, 2020)

e-Print: [2007.14300](#) [hep-ph]

## Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider

Tao Han (Pittsburgh U.), Da Liu (UC, Davis, QMAP), Ian Low (Northwestern U. and Argonne), Xing Wang (UC, San Diego) (Aug 27, 2020)

e-Print: [2008.12204](#) [hep-ph]

## WIMPs at High Energy Muon Colliders

Tao Han (Pittsburgh U.), Zhen Liu (Maryland U.), Lian-Tao Wang (Chicago U., EFI and Chicago U., KICP), Xing Wang (UC, San Diego) (Sep 23, 2020)

e-Print: [2009.11287](#) [hep-ph]

## Muon $g - 2$ at multi-TeV muon collider

Wen Yin (Tokyo U. and KAIST, Taejeon), Masahiro Yamaguchi (Tohoku U.) (Dec 7, 2020)

e-Print: [2012.03928](#) [hep-ph]

 pdf  cite

[arXiv:2101.10334](#) [pdf, other]

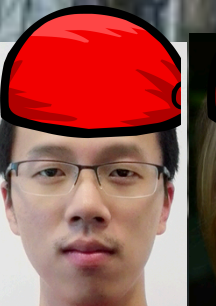
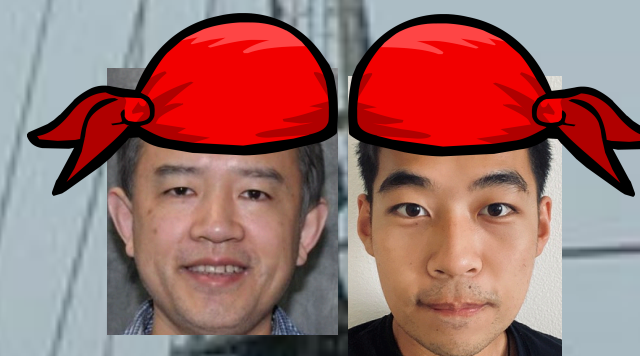
## A No-Lose Theorem for Discovering the New Physics of $(g - 2)_\mu$ at Muon Colliders

Rodolfo Capdevilla, David Curtin, Yonatan Kahn, Gordan Krnjaic

Comments: 54 pages, 9 figures, 5 tables

Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)

+ MANY LOIs for Snowmass and other ideas



**WANTED**

**MORE**

**THEORISTS  
TO WORK ON  
MUON COLLIDERS**

**REWARD: MORE  
PAPERS ON ARXIV**

# Credit where credit is due... some have been there from the beginning



**s channel Higgs boson production at a muon muon collider** #65

[Vernon D. Barger](#) (Wisconsin U., Madison), [M.S. Berger](#) (Indiana U.), [J.F. Gunion](#) (UC, Davis), [Tao Han](#) (UC, Davis) (Apr 21, 1995)

Published in: *Phys.Rev.Lett.* 75 (1995) 1462-1465 • e-Print: [hep-ph/9504330](#) [hep-ph]

pdf

DOI

cite

150 citations



Tao Han TASI 2004



**Electroweak couplings of the Higgs boson at a multi-TeV muon collider** #5

[Tao Han](#) (Pittsburgh U.), [Da Liu](#) (UC, Davis, QMAP), [Ian Low](#) (Northwestern U. and Argonne), [Xing Wang](#) (UC, San Diego) (Aug 27, 2020)

Published in: *Phys.Rev.D* 103 (2021) 1, 013002 • e-Print: [2008.12204](#) [hep-ph]

pdf

DOI

cite

9 citations

Tao Han current DPF chair

**Theorists have the opportunity to play a  
BIG  
role in making the physics case for this Snowmass/P5**

**So what's caused the change and what do  
we want to accomplish?**

# Joint AF-EF Meeting on Future coliders : Day 1

📅 Wednesday Jun 24, 2020, 9:00 AM → 10:00 PM US/Central

👤 Dmitri Denisov (Fermilab) , Meenakshi Narain (Brown University) , Vladimir Shiltsev (FNAL)

## Energy Frontier

- EF science goals currently envision two types of future colliders (in arbitrary order)
  - Higgs (and other known elementary particles) factory
  - Next high energy frontier machine
- Discoveries at the Energy Frontier are intricately linked to the progress in accelerators.

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Meshes well with *last* P5 science drivers

# Last Snowmass the Muon Collider physics case lived mostly on the Higgs Factory side

Potential precision of a direct measurement of the Higgs boson total width at a muon collider

Tao Han (Pittsburgh U.), Zhen Liu (Pittsburgh U.) (Oct 30, 2012)

Published in: *Phys.Rev.D* 87 (2013) 3, 033007 • e-Print: [1210.7803](#) [hep-ph]

Super cool option for super-compact Higgs factory and getting total width

However even in modern reviews it's not compared to other options

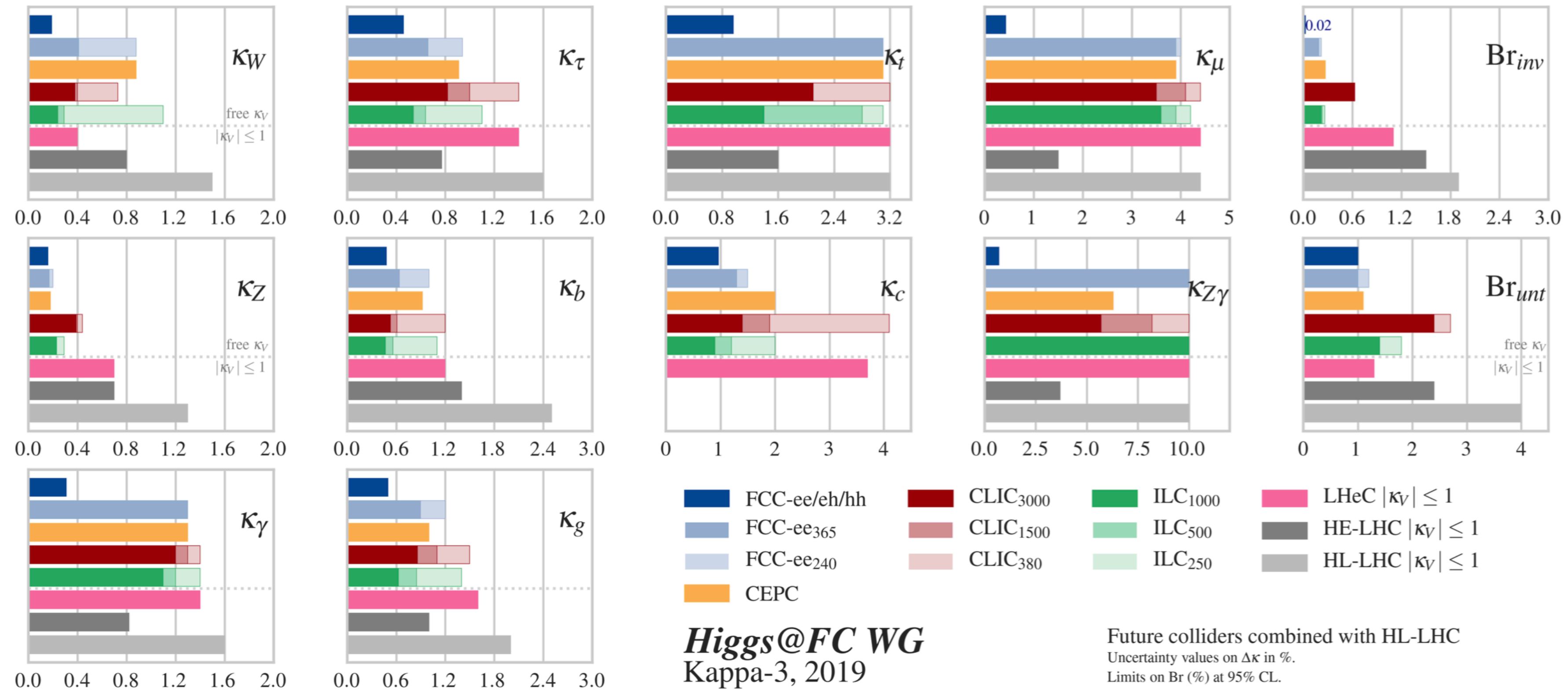


Fig. 3.8: Expected relative precision of the  $\kappa$  parameters and 95% CL upper limits on the branching ratios to invisible and untagged particles for the various colliders. All values are given in %. For the hadron colliders, a constraint  $|\kappa_V| \leq 1$  is applied, and all future colliders are combined with HL-LHC. For colliders with several proposed energy stages it is also assumed that data taken in later years are combined with data taken earlier. Figure is from Ref. [39].

**Nowadays the focus is more on the multi-TeV muon colliders**

**This brings in a lot more of the theory community since Energy wins when trying to answer so many of our outstanding theory questions when reconciled with existing data  
(hence why so much 100 TeV work)**

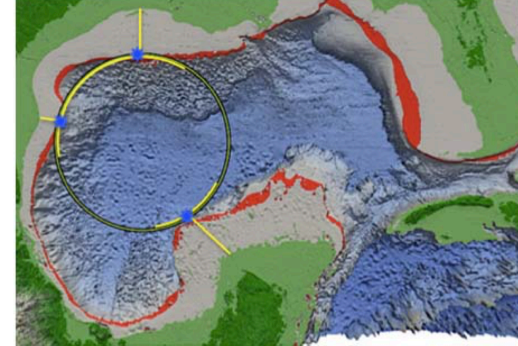


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron

?

Collider in the Sea: Vision for a 500 TeV World Laboratory

Physics  
Potential

$\mu$  -collider e w/PWFA 30 TeV

FCC-hh/SPPC

$\mu$ -collider 14 TeV

CLIC

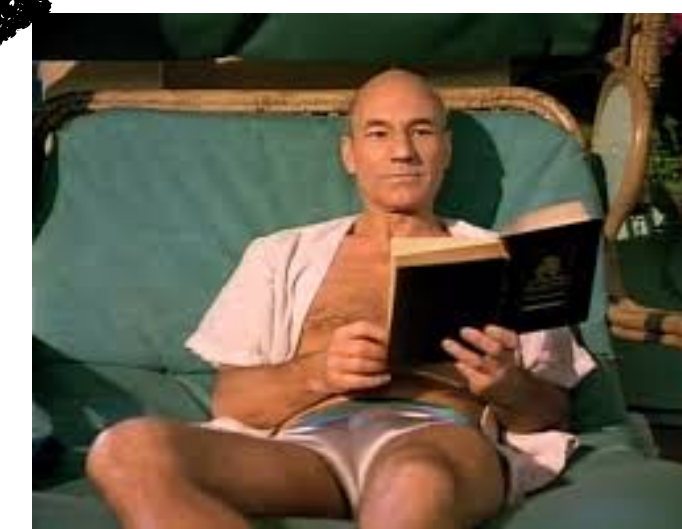
FCC-ee/CEPC

ILC

$\mu$ -collider 125



R&D attractiveness



# Nevertheless as Foundational Physics Potential Cases Go...

## More Energy = More Money



HIGGS



UNKNOWN

*If you want a **guaranteed** return it's a lot harder*

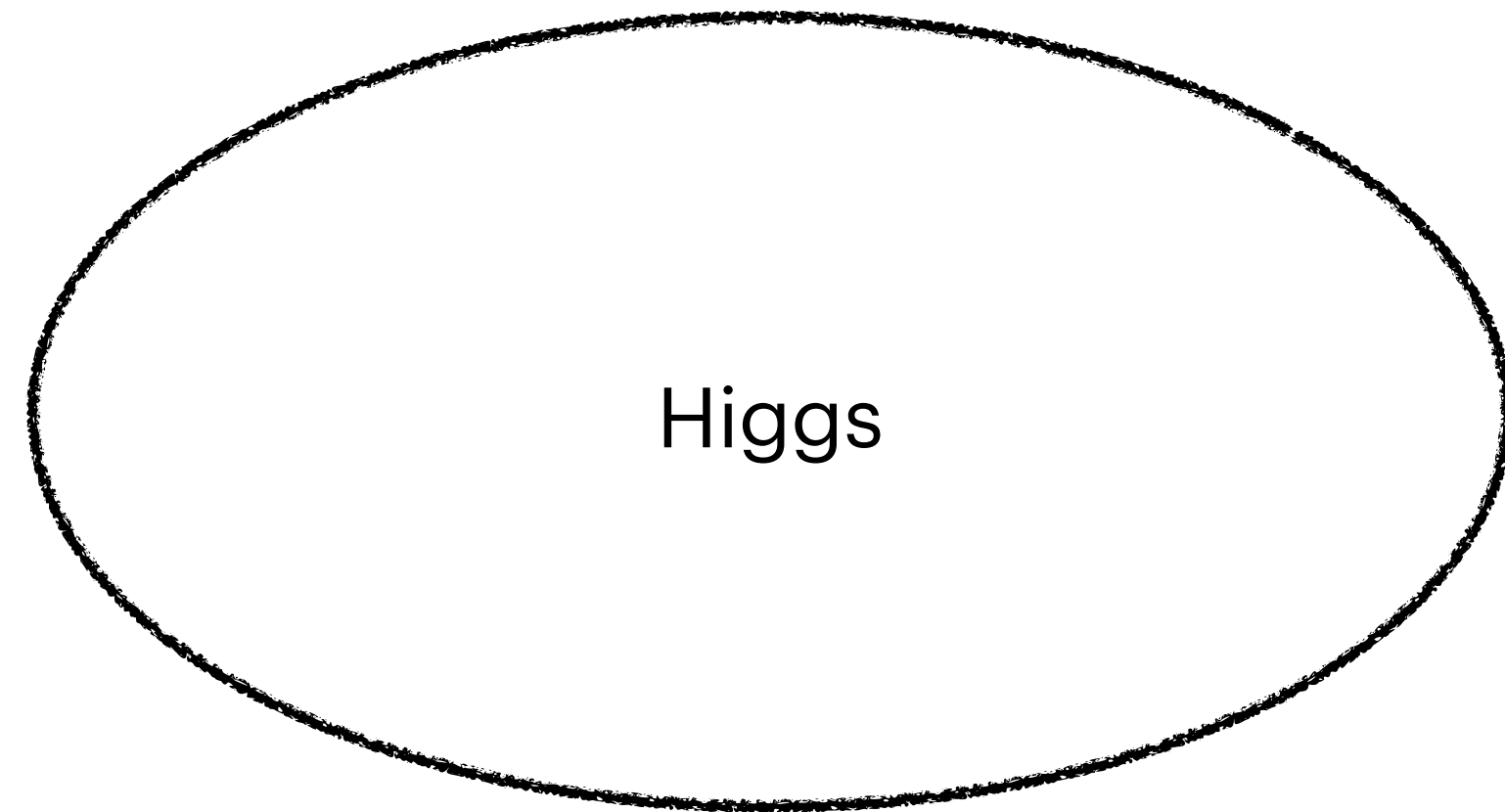
**An interesting aspect that hasn't been explored as much,  
(and where a lot of progress can be made) is that a multi-  
TeV muon collider can potentially win for the Higgs as well!**

**Despite Higgs Factories Being a Major Push...**

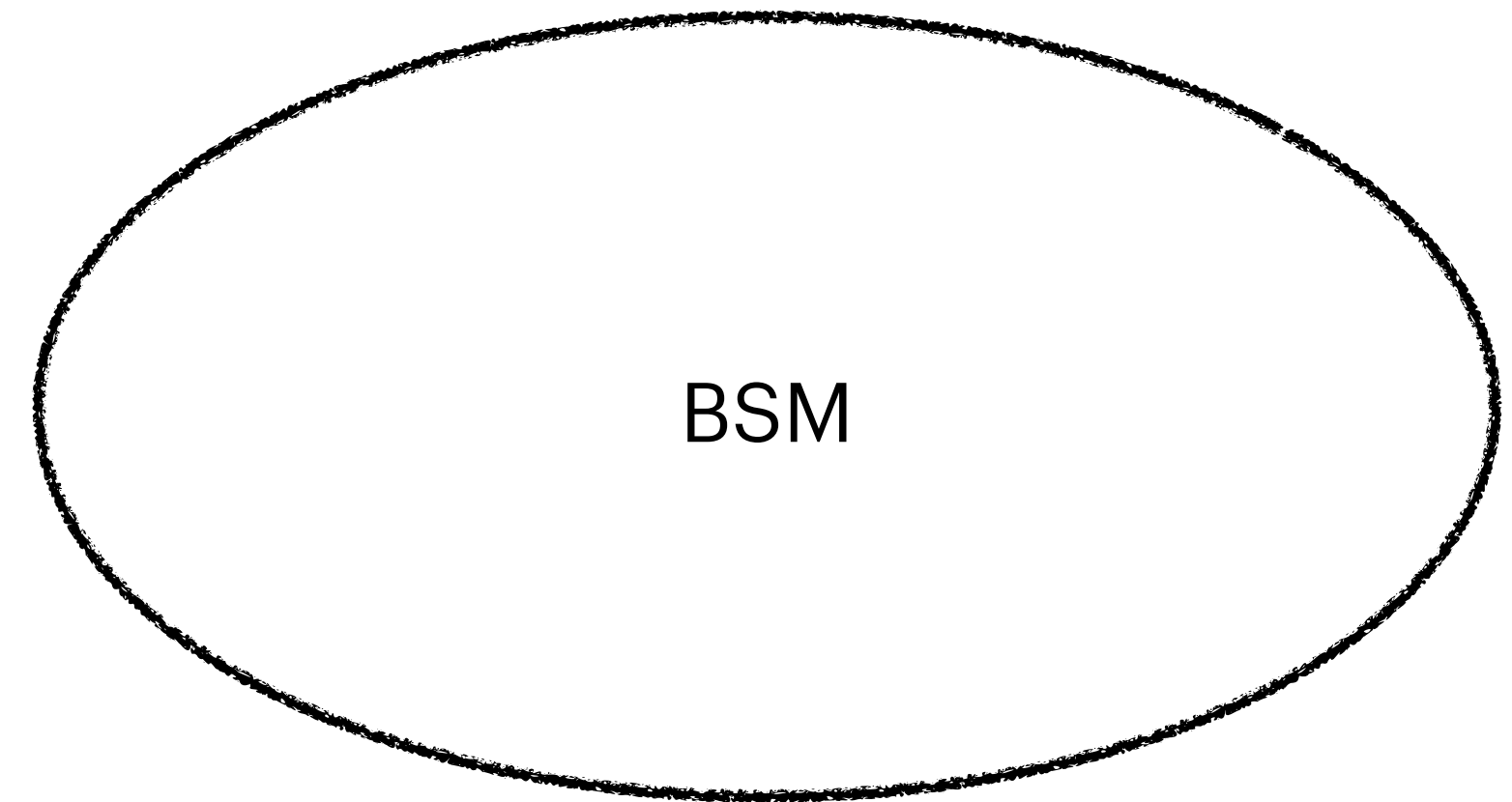
**Many properties of the Higgs will still have  $O(1)$  uncertainty or worse!**

**For example Higgs self couplings, and light flavor**

# COMPLETE THE SM!

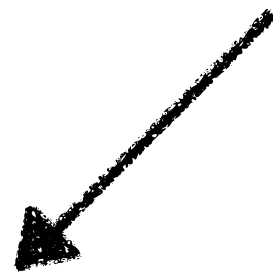


Higgs

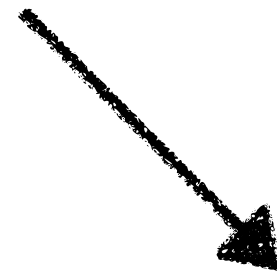


BSM

Biggest open areas post HL-LHC



Self couplings!



Light Flavor!

*Needs Energy*

*Needs Precision*

*Both need a lot of Higgs!*

# How Many Higgs??

## Take this with many grains of salt...

HL-LHC     $\sim .35 \times 10^9$     End of LHC ~ O(100) million Higgses!

ILC250/350     $\sim .6 \times 10^6$   
FCC-ee 240/365     $\sim 1.2 \times 10^6$   
CEPC 240     $\sim 1.1 \times 10^6$   
CLIC-380     $\sim .2 \times 10^6$

} Low energy e+e- Higgs factories  
~ 1 million Higgs

ILC500/1000     $\sim 4.5 \times 10^6$   
CLIC 1500/3000     $\sim 3.4 \times 10^6$

} Moderate energy e+e- Higgs factories  
~ few million Higgs

FCC-hh     $\sim 27 \times 10^9$     27 billion Higgses

500 TeV 50/ab     $\sim 400 \times 10^9$     Can approach a trillion Higgs

Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you *could* do if you could exploit them all!

ESG run plans 1905.03764

Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%] [ $e^-/e^+$ ]	N(Det.)	$\mathcal{L}_{\text{inst}}$ [ $10^{34}$ ] $\text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ [ $\text{ab}^{-1}$ ]	Time [years]	Refs.	Abbreviation
HL-LHC	$pp$	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	$pp$	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh <sup>(*)</sup>	$pp$	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	$ee$	$M_Z$	0/0	2	100/200	150	4	[1]	FCC-ee <sub>240</sub> FCC-ee <sub>365</sub> (1y SD before $2m_{top}$ run)
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		
							(+1)		
ILC	$ee$	250 GeV	$\pm 80/\pm 30$	1	1.35/2.7	2.0	11.5	[3, 14]	ILC <sub>250</sub> ILC <sub>350</sub> ILC <sub>500</sub> (1y SD after 250 GeV run) ILC <sub>1000</sub> (1-2y SD after 500 GeV run)
		350 GeV	$\pm 80/\pm 30$	1	1.6	0.2	1		
		500 GeV	$\pm 80/\pm 30$	1	1.8/3.6	4.0	8.5		
							(+1)		
		1000 GeV	$\pm 80/\pm 20$	1	3.6/7.2	8.0	8.5 (+1-2)		
CEPC	$ee$	$M_Z$	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	$ee$	380 GeV	$\pm 80/0$	1	1.5	1.0	8	[15]	CLIC <sub>380</sub> CLIC <sub>1500</sub> CLIC <sub>3000</sub> (2y SDs between energy stages)
		1.5 TeV	$\pm 80/0$	1	3.7	2.5	7		
		3.0 TeV	$\pm 80/0$	1	6.0	5.0	8		
							(+4)		
LHeC	$ep$	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	$ep$	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	$ep$	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Speculative high energy options (run plans specified here)

### Muon (or electron colliders)

6 TeV 4/ab     $\sim 3.2 \times 10^6$

10 TeV 10/ab     $\sim 9.5 \times 10^6$

14 TeV 20/ab     $\sim 22 \times 10^6$

30 TeV 90/ab     $\sim .12 \times 10^9$

100 TeV 100/ab     $\sim .18 \times 10^9$

Millions to 100s of millions

### Collider in the sea

**Figure of merit LEP had 17 Million Zs**

# How Many Higgs??

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HL-LHC  $\sim .35 \times 10^9$  End of LHC ~ O(100) million Higgses!

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Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you could do if you could exploit them all!

Moreover if you want to produce multi-Higgs you **NEED** the higher energy

ESG run plans 1905.03764

Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%] [ $e^-/e^+$ ]	N(Det.)	$\mathcal{L}_{\text{inst}}$ [ $10^{34}$ ] $\text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ [ $\text{ab}^{-1}$ ]	Time [years]	Refs.	Abbreviation
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		240 GeV	0/0	2	7	5	3		
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							(+1)		
ILC	$ee$	250 GeV	$\pm 80/\pm 30$	1	1.35/2.7	2.0	11.5	[3, 14]	ILC <sub>250</sub> ILC <sub>350</sub> ILC <sub>500</sub> (1y SD after 250 GeV run) ILC <sub>1000</sub> (1-2y SD after 500 GeV run)
		350 GeV	$\pm 80/\pm 30$	1	1.6	0.2	1		
		500 GeV	$\pm 80/\pm 30$	1	1.8/3.6	4.0	8.5		
							(+1)		
		1000 GeV	$\pm 80/\pm 20$	1	3.6/7.2	8.0	8.5		
CEPC	$ee$	$M_Z$	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	$ee$	380 GeV	$\pm 80/0$	1	1.5	1.0	8	[15]	CLIC <sub>380</sub> CLIC <sub>1500</sub> CLIC <sub>3000</sub> (2y SDs between energy stages)
		1.5 TeV	$\pm 80/0$	1	3.7	2.5	7		
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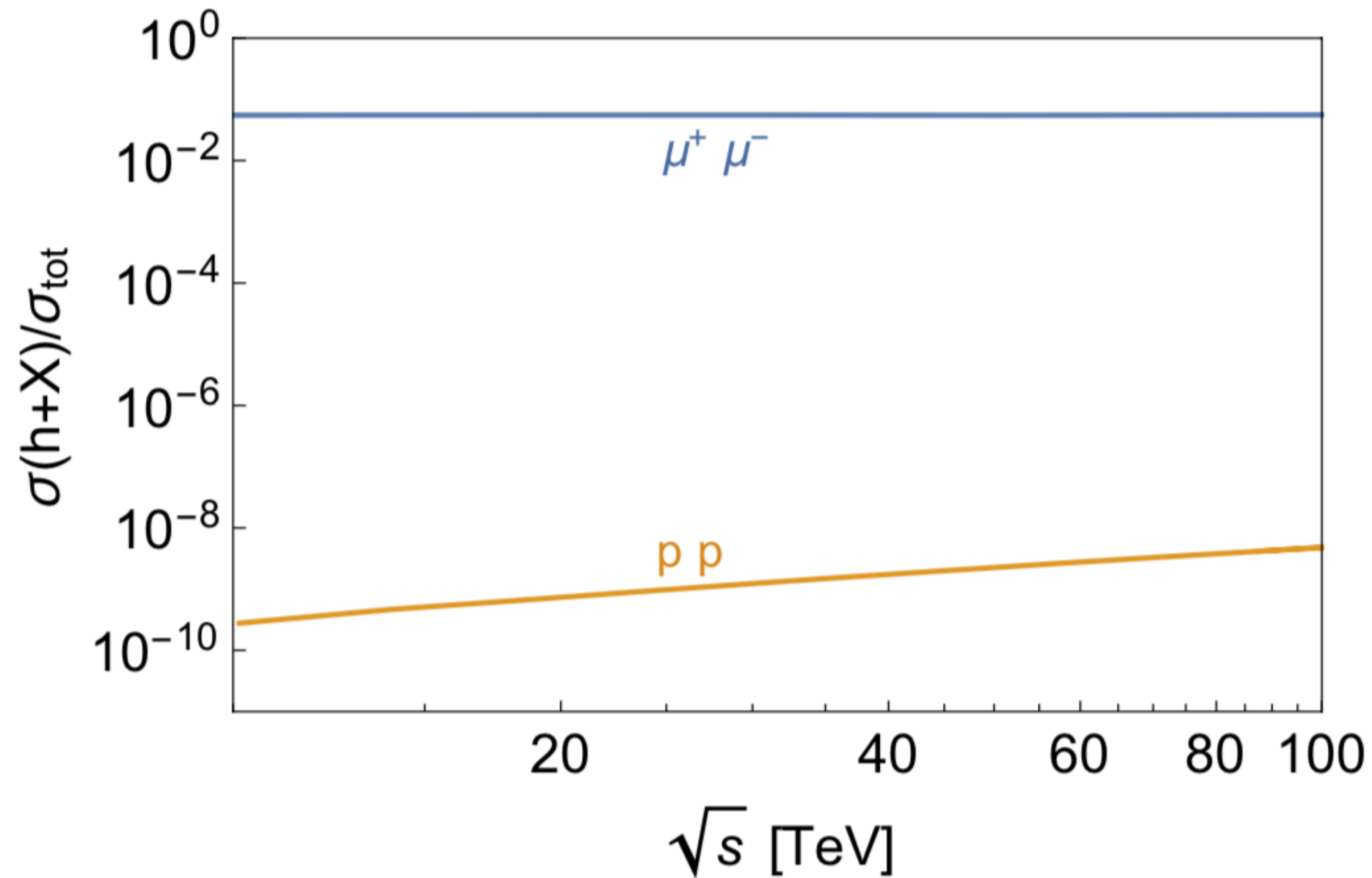
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Millions to 100s of millions

### Collider in the sea

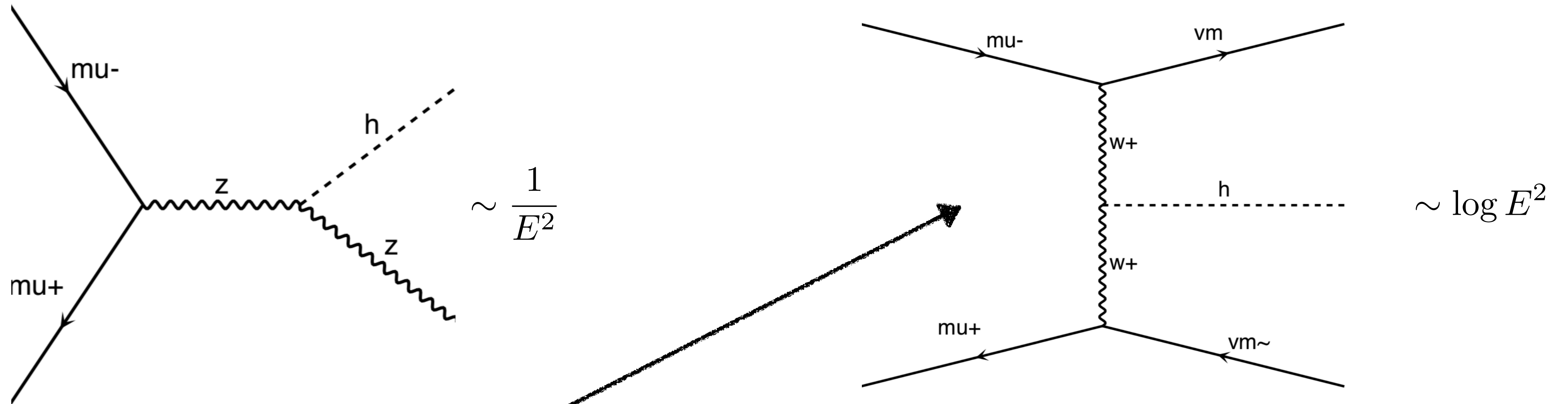


**Precision needs precision, but leptons give you a head start compared to hadrons!**

**Why do high energy leptons produce so many  
Higgs particles?**

# Muon colliders are gauge boson colliders

That's why a lot of this physics case ports directly to high energy e, mu, gamma colliders

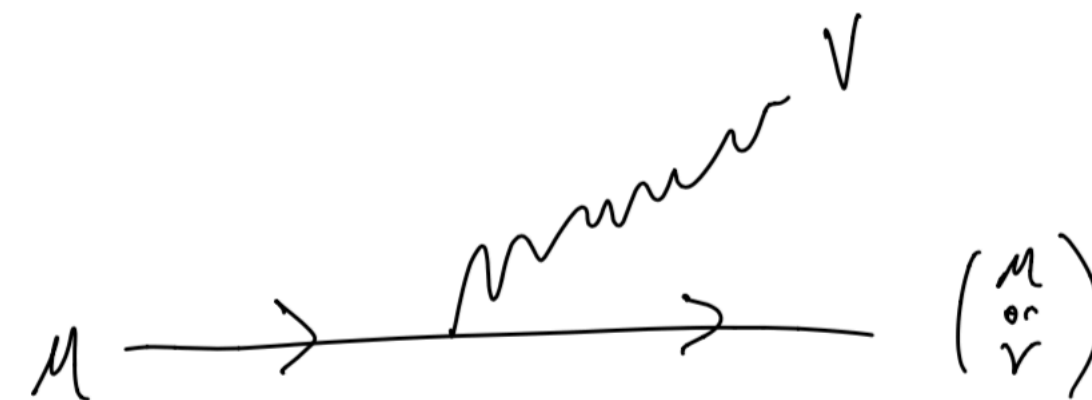
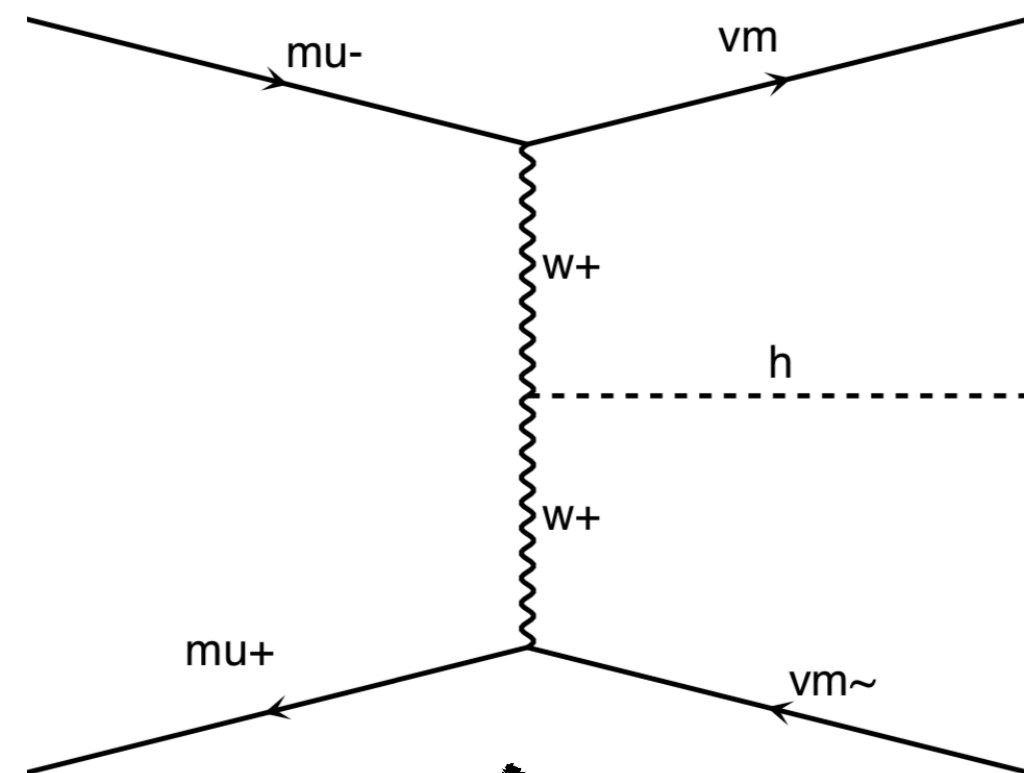


Winner at moderate energies!

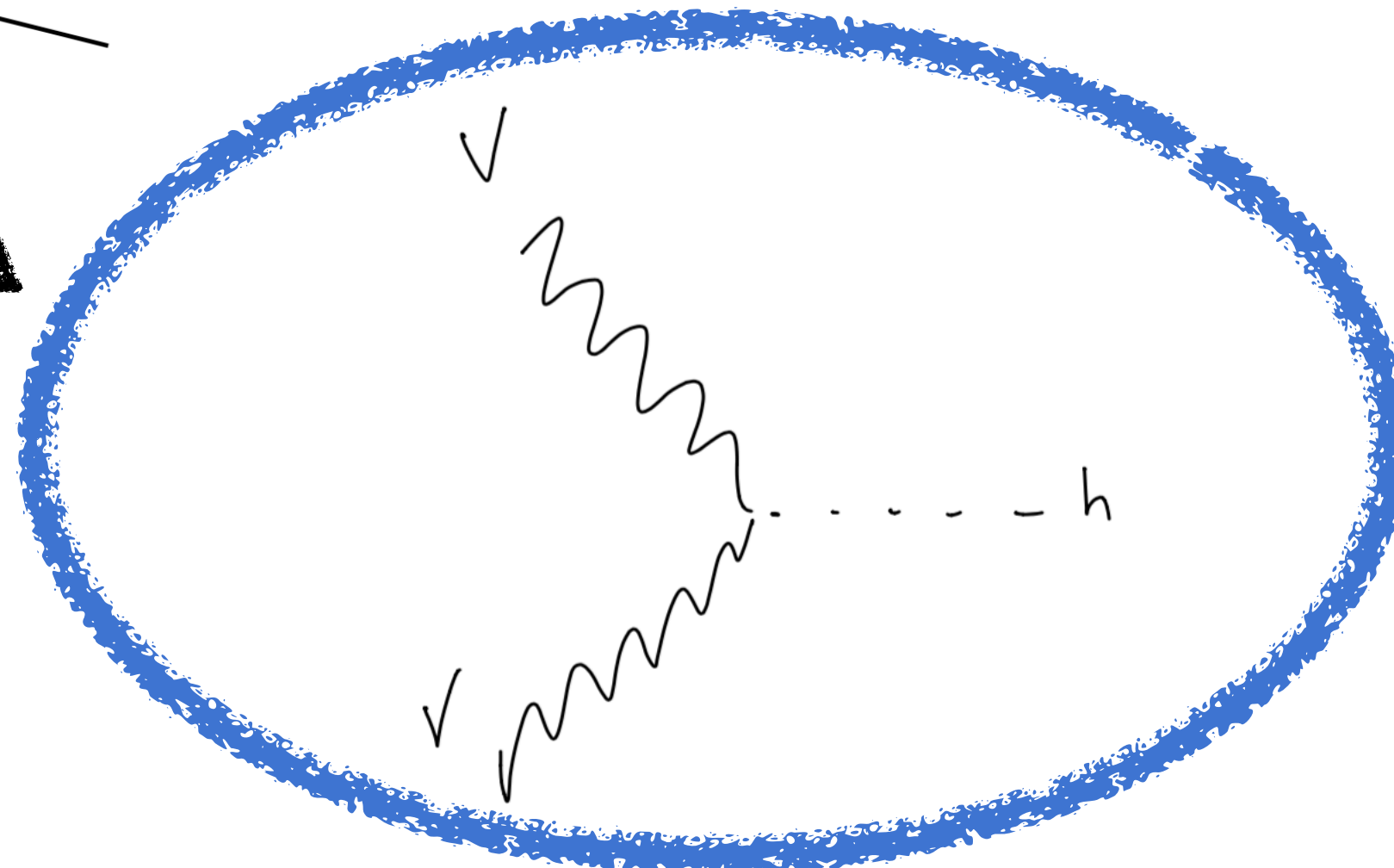
Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)

# Muon colliders are gauge boson colliders

Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)



Vector Boson really wants to be soft or collinear....



# Multi-Higgs results

$\sqrt{s}$ (lumi.)	3 TeV (1 ab <sup>-1</sup> )	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
$WWH$ ( $\Delta\kappa_W$ )	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
$ZZH$ ( $\Delta\kappa_Z$ )	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ( $\Delta\kappa_{W_2}$ )	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
$HHH$ ( $\Delta\kappa_3$ )	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 4: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

2008.12204 T. Han, D. Liu, I. Low, X. Wang

$\sqrt{s}$ (TeV)	Lumi (ab <sup>-1</sup> )	Constraints on $\delta_4$ (with $\delta_3 = 0$ )		
		x-sec only, acceptance cuts		
		1 $\sigma$	2 $\sigma$	3 $\sigma$
6	12	[−0.50, 0.70]	[−0.74, 0.95]	[−0.93, 1.15]
10	20	[−0.37, 0.54]	[−0.55, 0.72]	[−0.69, 0.85]
14	33	[−0.28, 0.43]	[−0.42, 0.58]	[−0.52, 0.68]
30	100	[−0.15, 0.30]	[−0.24, 0.38]	[−0.30, 0.45]
3	100	[−0.34, 0.64]	[−0.53, 0.82]	[−0.67, 0.97]

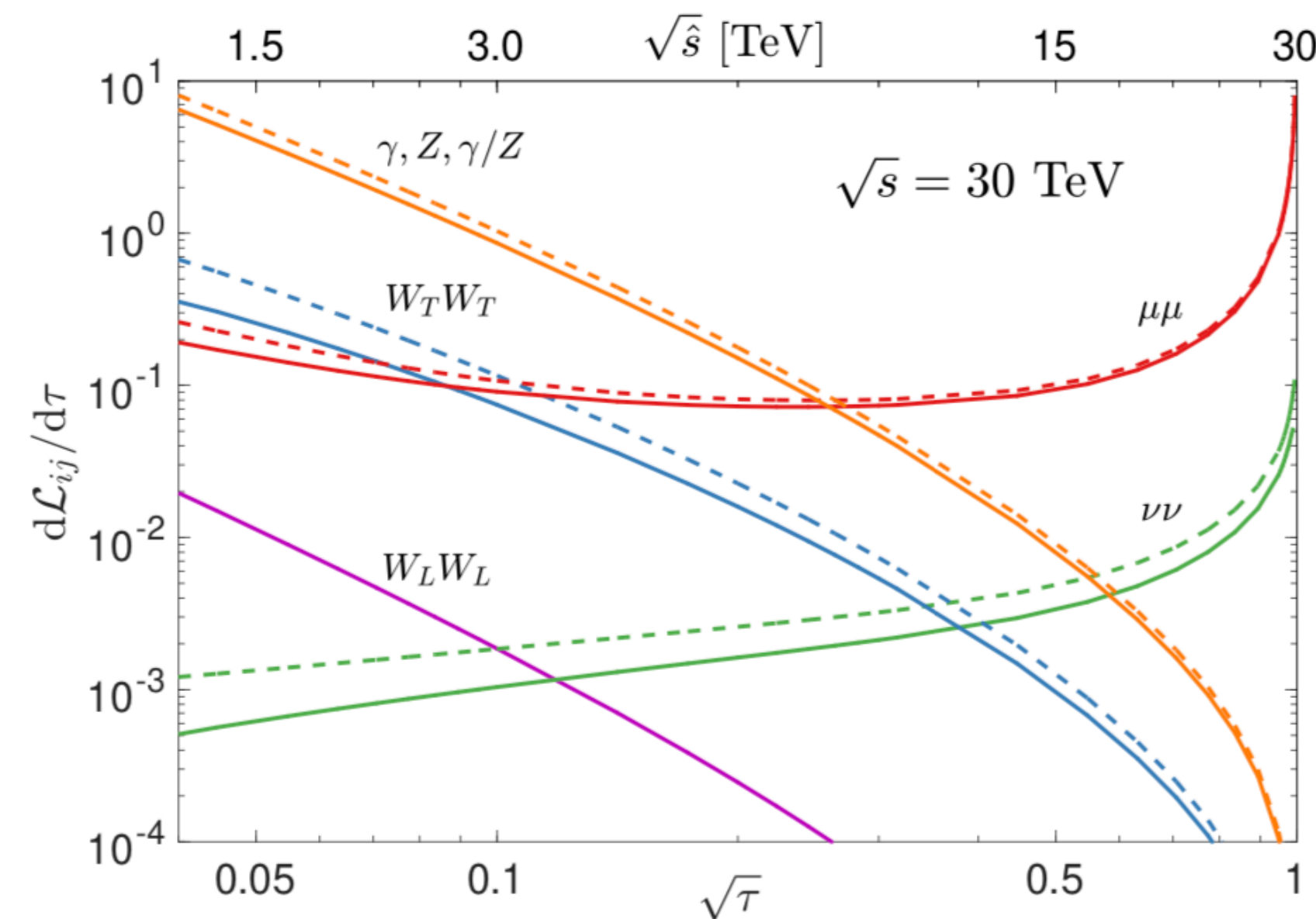
Table 6: Constraints on  $\delta_4$  ( $\delta_3 = 0$ ) for the c.m. energies and the instantaneous luminosities in table [1] once the geometric acceptance cuts  $p_T > 20$  GeV and  $|\eta| < 3$  are applied to the Higgs decay products. The bounds are obtained from the total expected cross sections for the process  $\mu^+\mu^- \rightarrow HHH\nu\bar{\nu}$ . The Higgs bosons are produced on-shell and decayed to  $b\bar{b}$  pairs but no branching ratio is applied.

Triple Higgs bounds!!!

2003.13628 M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, X. Zhao

HE muon collider = Precision + Energy?

# Muon colliders are *more than* gauge boson colliders



2007.14300 T. Han, Y. Ma, K. Xie

FIG. 2. Distributions for (a) EW PDFs  $f_i(x)$  and, (b) parton luminosities  $dL_{ij}/d\tau$  versus  $\sqrt{\tau}$  for  $\sqrt{s} = 30$  TeV with a factorization scale  $Q = \sqrt{\hat{s}}/2$  (solid) and  $\sqrt{\hat{s}}$  (dashed).

You get tons of Gauge Bosons at low  $x$  - like gluons at a Hadron collider

BUT

you **ALSO** get muons peaking at  $x \sim 1$  *unlike* quarks at hadron colliders!!

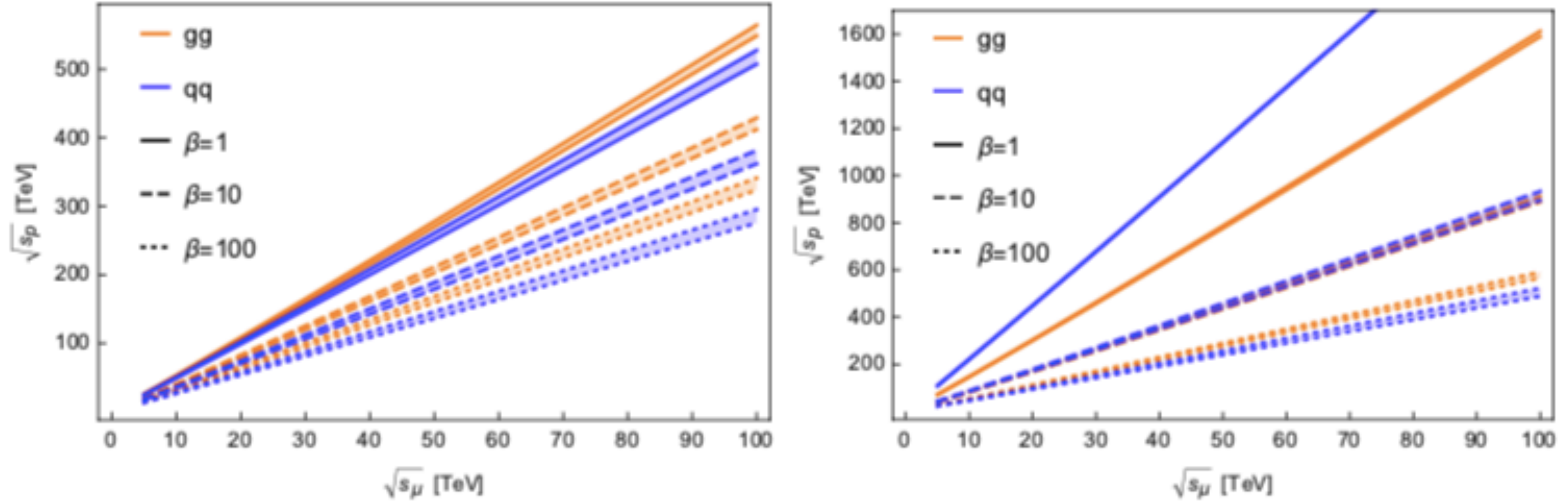
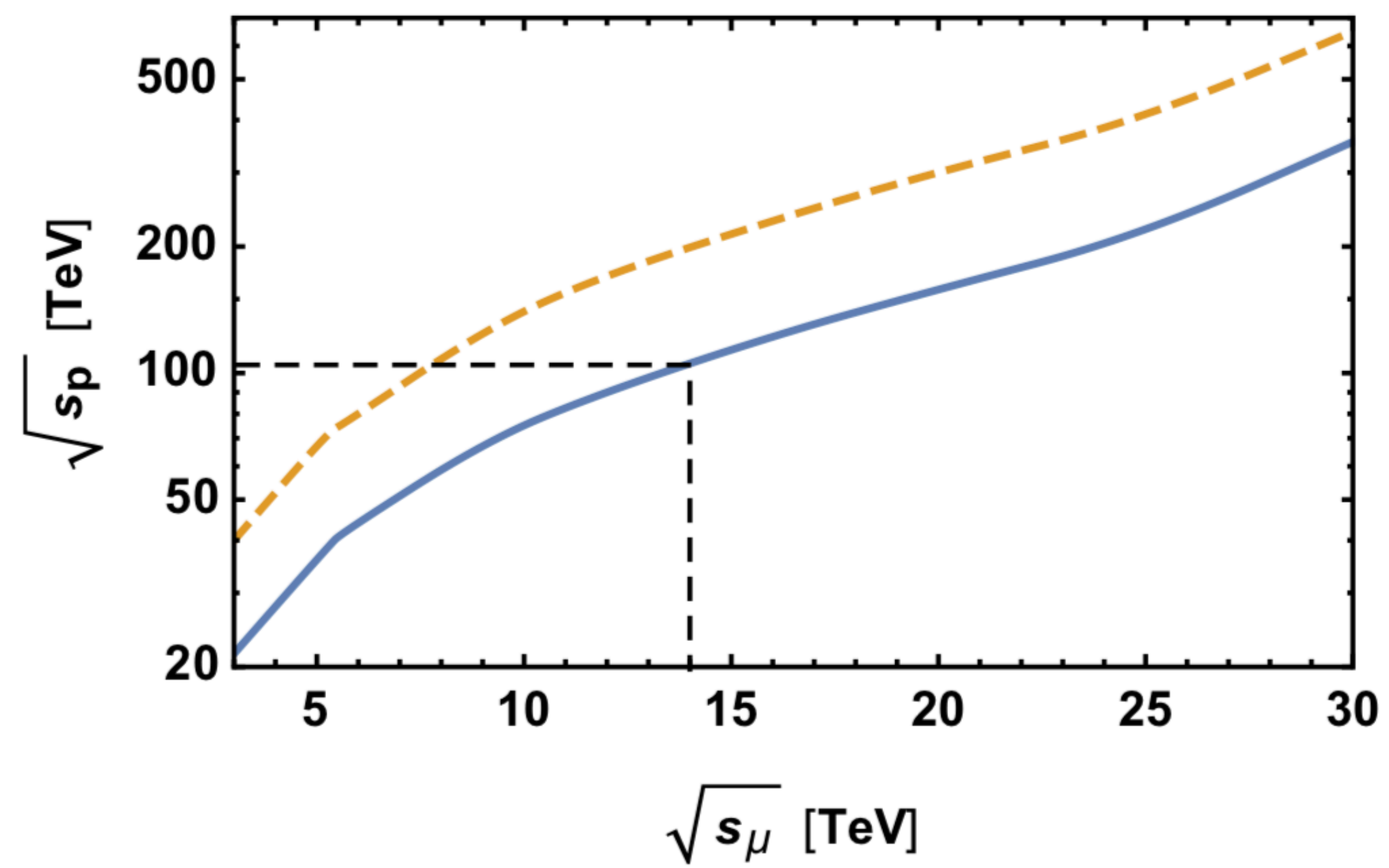


Figure 1: The c.m. energy  $\sqrt{s_p}$  in TeV at a proton-proton collider versus  $\sqrt{s_\mu}$  in TeV at a muon collider, which yield equivalent cross sections. Curves correspond to production via a  $gg$  (orange) or  $q\bar{q}$  (blue) initial state at the proton-proton collider, while production at the muon collider is determined by  $\mu^+\mu^-$ . The partonic cross sections are related by  $\beta \equiv [\hat{\sigma}]_p/[\hat{\sigma}]_\mu$ . The bands correspond to two different choices of proton PDF sets, NNPDF3.0 LO (as in [1]) and CT18NNLO. Left:  $2 \rightarrow 1$  scattering. Right:  $2 \rightarrow 2$  scattering.



Similar to what's in 1901.06150 Delahaye et al

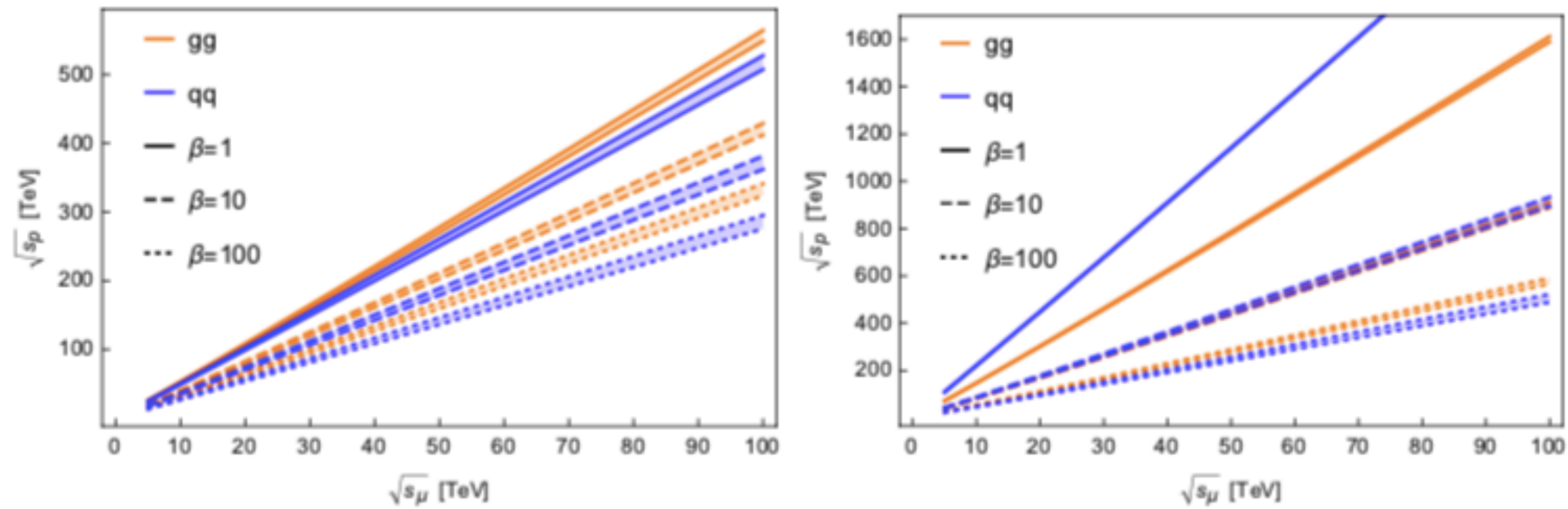


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Roughly there is equivalence to a 100 TeV pp collider for

$$2 \rightarrow 1$$

$$\sqrt{s_\mu} \sim 20 \text{ TeV}$$

$$2 \rightarrow 2$$

$$\sqrt{s_\mu} \sim 5 - 7 \text{ TeV}$$

The devil is in the details always... but O(10) TeV is also interesting from Higgs

# Lots of BSM Targets

Electroweak Symmetry Breaking  
Electroweak Phase Transition  
Electroweak Baryogenesis  
Flavor

Naturalness

Dark Matter

Complementarity

# Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to “win the race”



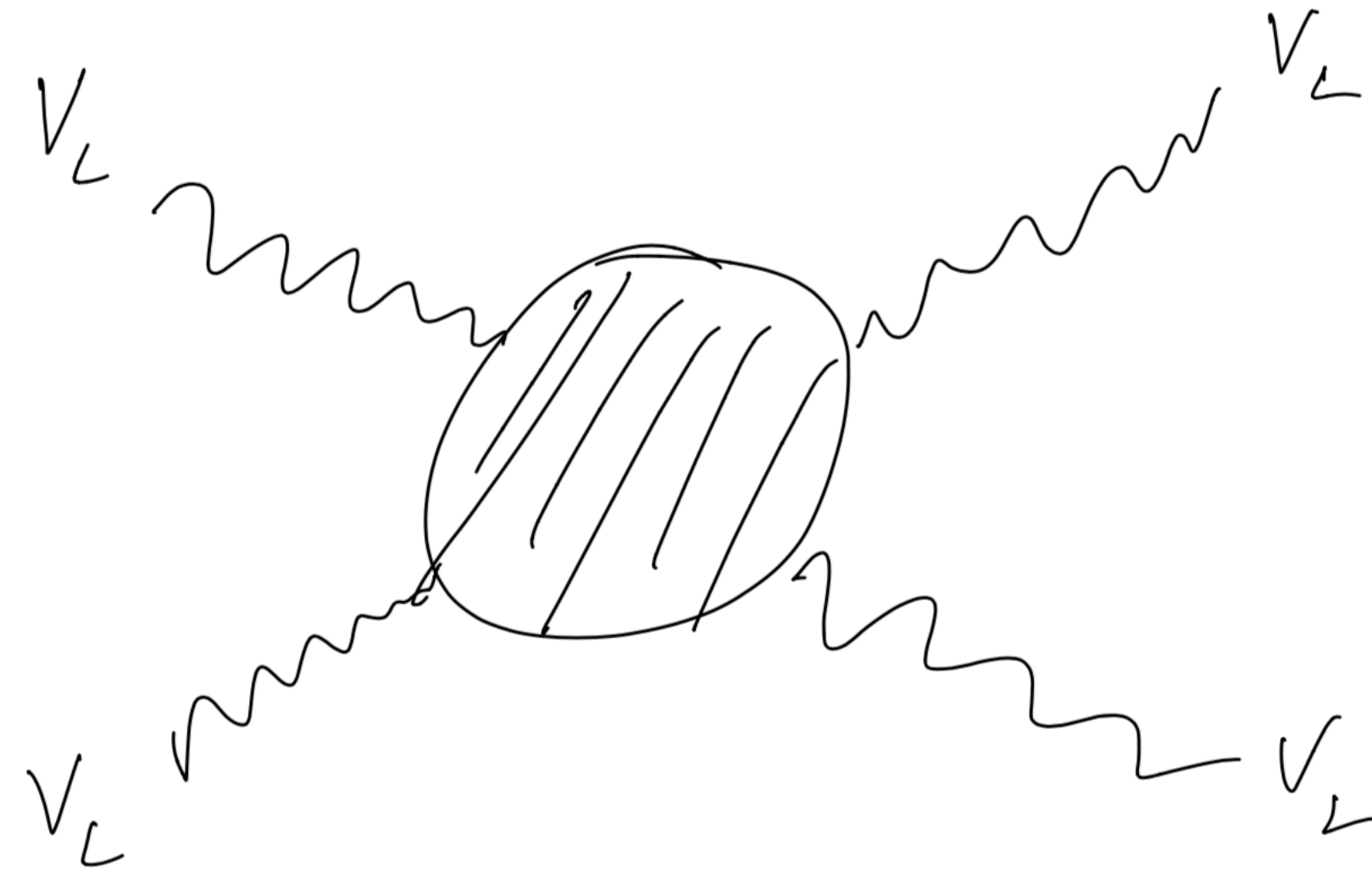
Nevertheless if we get indirect hints from existing  
or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

# What can you do with energy and EWSB?

## Perturbative Unitarity Bounds!

Lee-Quigg-Thacker Higgs mass bound



$$m_h \lesssim 1 \text{ TeV}$$

## The SM Higgs

- 
- These properties are very delicate
-

# What can you do with energy and EWSB?

These delicate cancellations persist all over the place!

For example a modified Top Yukawa...

$$\mathcal{M}(W_L^+ W_L^- \rightarrow t\bar{t})$$

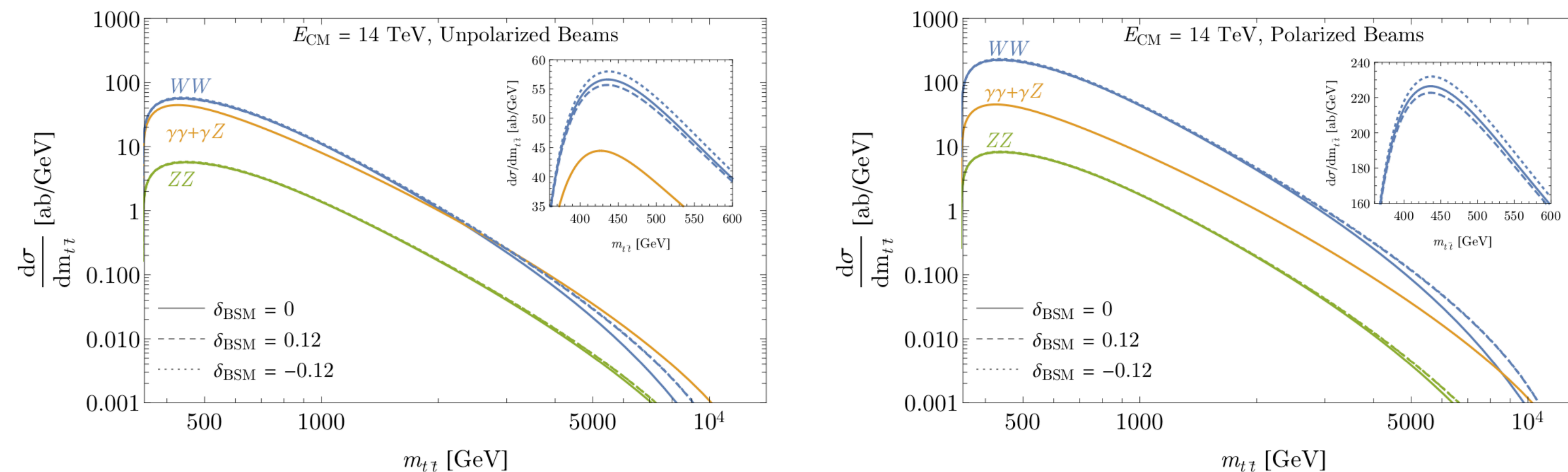


Figure 7: Differential cross section for  $\mu^+\mu^- \rightarrow t\bar{t} + X$  from different gauge boson fusion processes at a 14 TeV muon collider, with unpolarized beams (left) or fully polarized (left-handed  $\mu^-$  and right-handed  $\mu^+$ ) beams (right). At high energies, a deviation from the Standard Model top Yukawa leads to a significant increase in the rates for the  $W_L W_L \rightarrow t\bar{t}$  process. At low energies (visible in the insets), it produces either destructive interference ( $\delta_{\text{BSM}} > 0$ ) or constructive interference ( $\delta_{\text{BSM}} < 0$ ).

# What can you do with energy and EWSB?

These delicate cancellations persist all over the place!

For example a modified Top Yukawa...

$$\mathcal{M}(W_L^+ W_L^- \rightarrow t\bar{t})$$

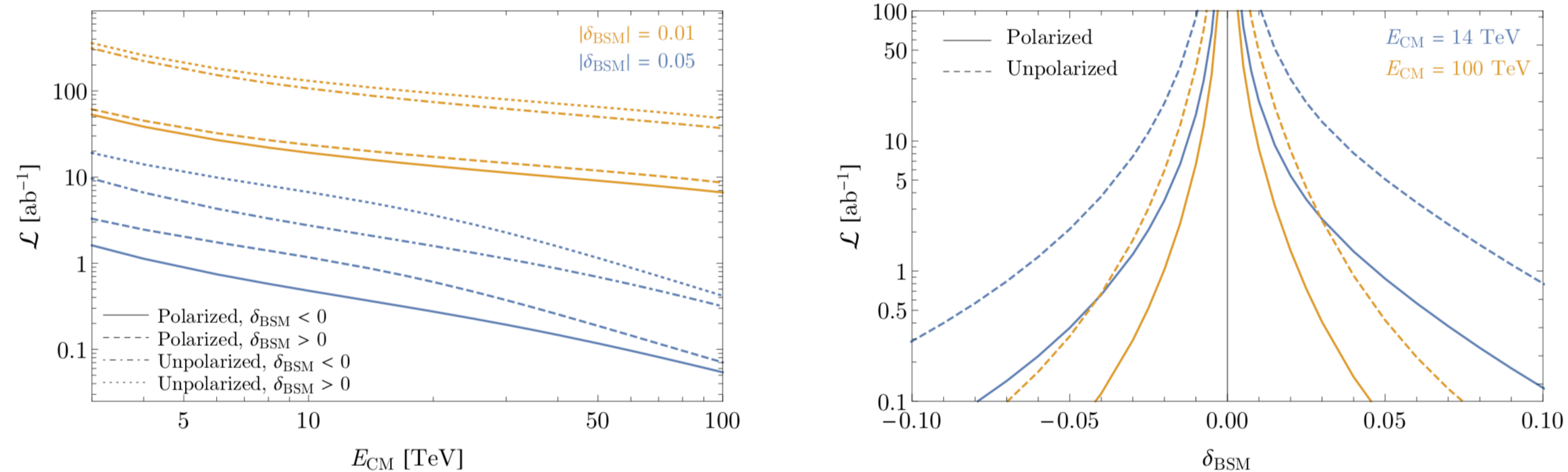
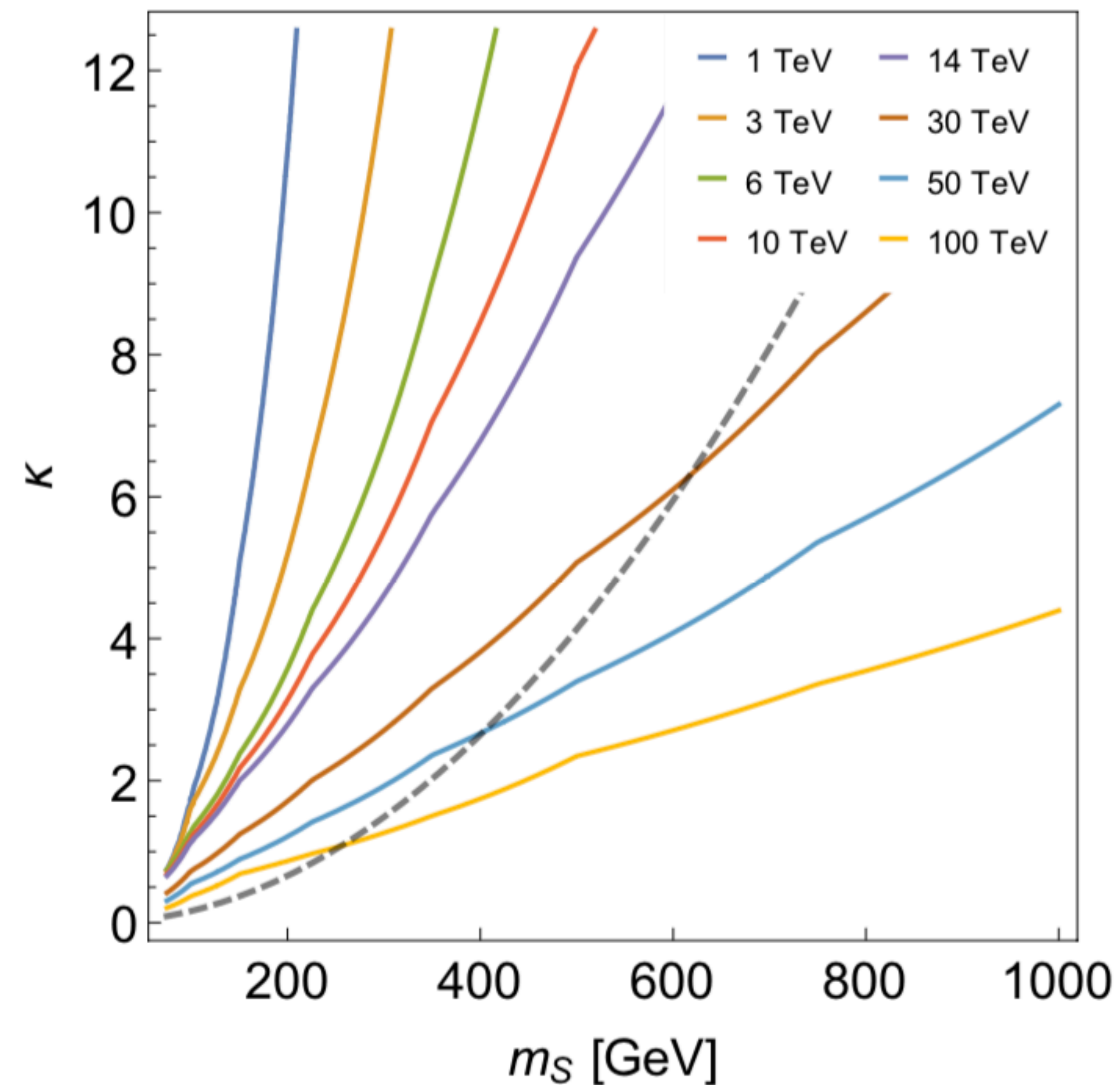


Figure 8: Luminosity needed to distinguish a modified top Yukawa coupling  $\delta_{\text{BSM}}$  from the Standard Model at  $2\sigma$  confidence, through the differential rate  $d\sigma/dm_{t\bar{t}}^2$  of the process  $\mu^+\mu^- \rightarrow t\bar{t} + X$ .

# The Nightmare Higgs Portal Scenario

## EWPT and Neutral Naturalness Prototype

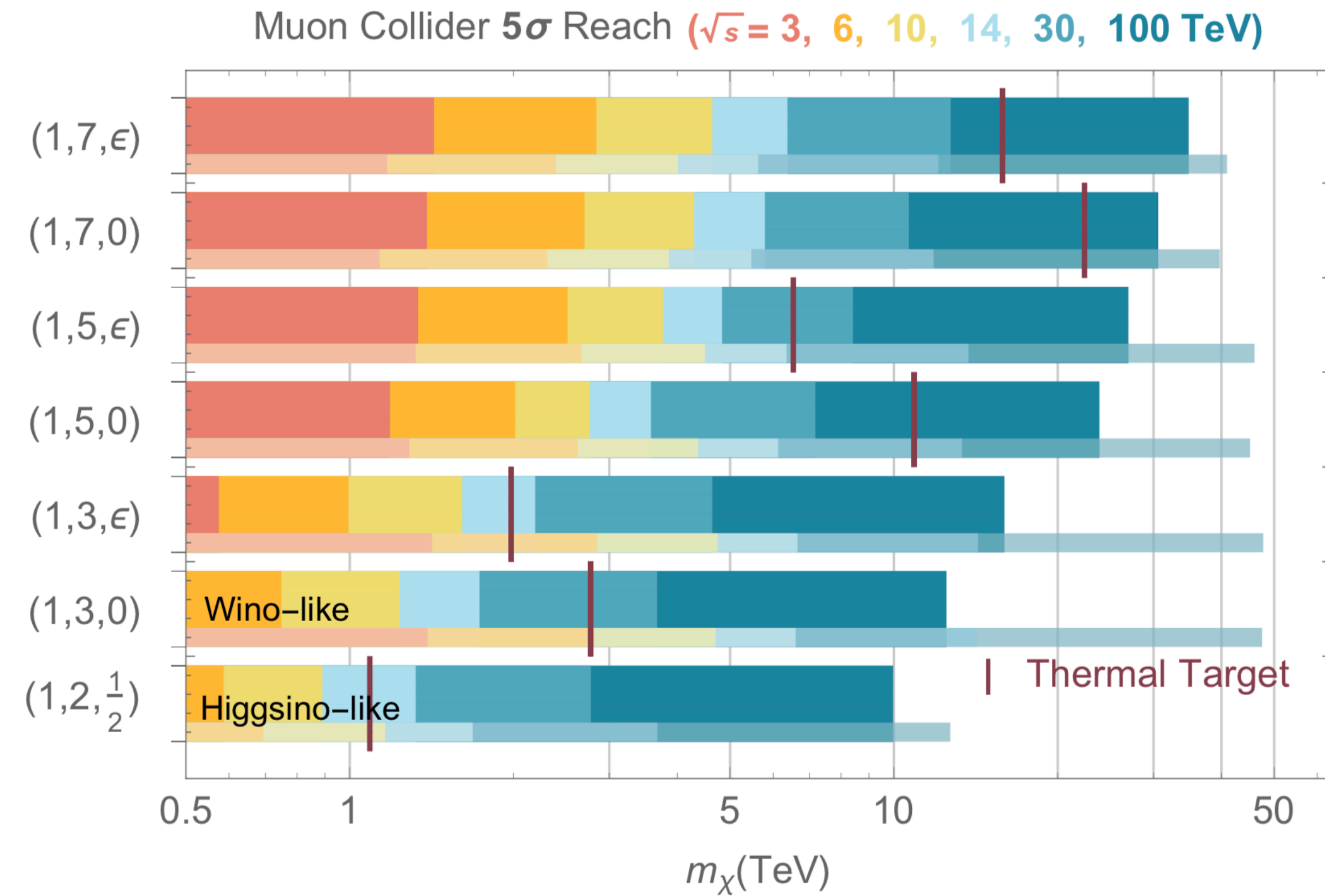
$$\mathcal{L} = \frac{1}{2}(\partial S)^2 - \frac{1}{2}M_S^2 S^2 - \kappa S^2 |H|^2$$



**Takeaway - even the hardest things are doable!**

# Dark Matter

## The WIMP *still* can be the DM



2009.11287 T. Han, Z. Liu, L. Wang, X. Wang

Figure 10: Summary of the discovery reaches of various muon collider running scenarios. The thicker bars represent the combined reach from missing mass searches through mono-photon, mono-muon, and VBF di-muon channels. The thinner and faint bars are our estimates of the mono-photon plus one disappearing track search. The burgundy vertical bars represent the thermal target for a given EW-multiplet model. More details, including the detailed reaches for each channels and different muon collider energies, can be found in Ref. [32].

# Naturalness Example

## Stop mass reach

rough background assumptions  
for collider up to 100 TeV

$$m_{\tilde{t}} \sim .9 \frac{\sqrt{s}}{2}$$

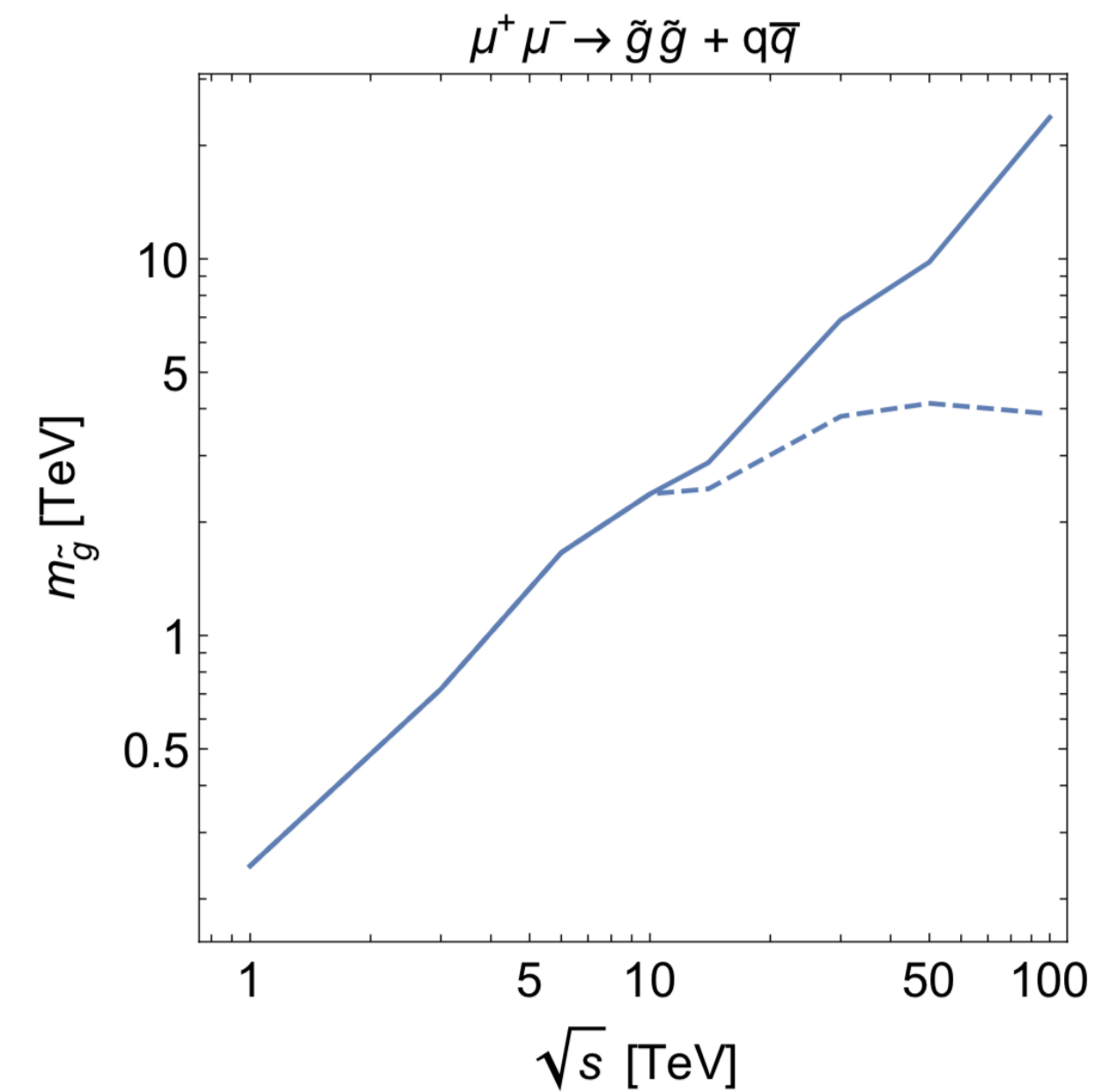


Figure 9: Gluino discovery reach from  $\mu^+ \mu^- \rightarrow \tilde{g} \tilde{g} + q \bar{q}$  as a function of  $\sqrt{s}$ , assuming “optimistic” (solid) and “conservative” (dashed) integrated luminosity scaling as detailed in the body of the text.

***Can even do gluinos at a lepton collider!***

# **What needs done (food for thought)**

More BSM physics analysis/reach

More Higgs analyses

We're just scratching the surface but the potential is already there!

There is a stronger machine/detector interplay for muon colliders, with this forum and the physics case we can understand the drivers and iterate

# If the outcome of Snowmass gives added \*realistic\* entries for muon colliders to the physics summary it would be a great goal for the forum

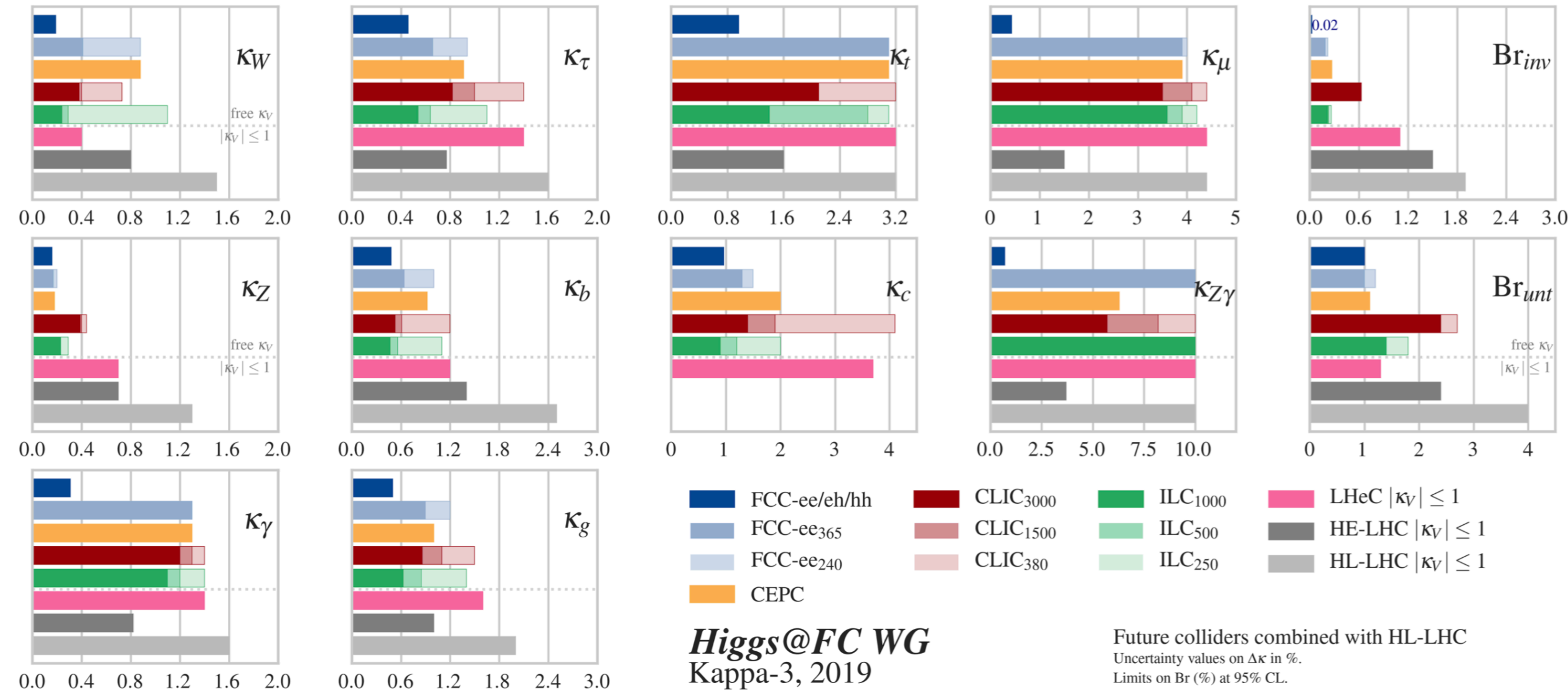
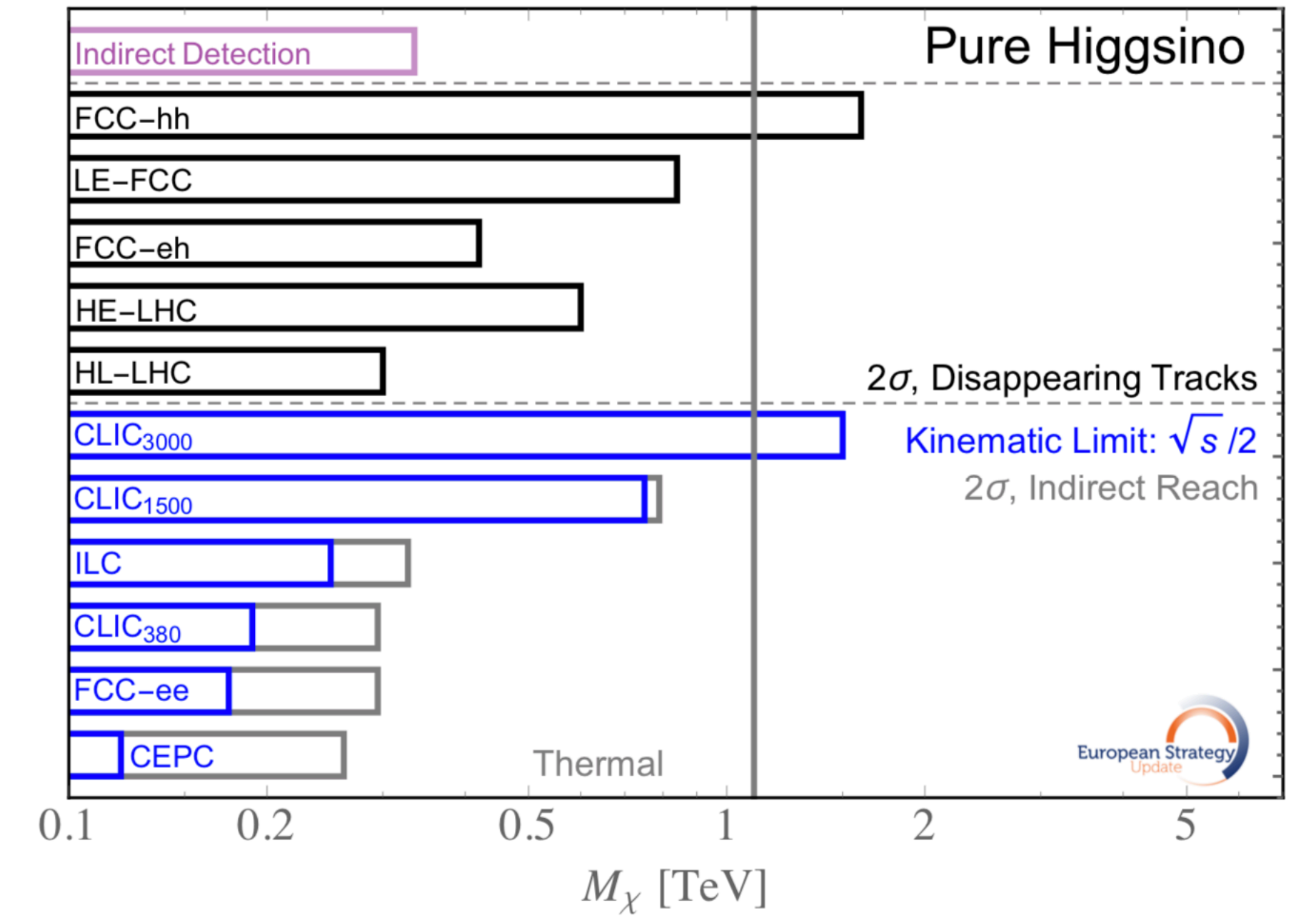


Fig. 3.8: Expected relative precision of the  $\kappa$  parameters and 95% CL upper limits on the branching ratios to invisible and untagged particles for the various colliders. All values are given in %. For the hadron colliders, a constraint  $|\kappa_V| \leq 1$  is applied, and all future colliders are combined with HL-LHC. For colliders with several proposed energy stages it is also assumed that data taken in later years are combined with data taken earlier. Figure is from Ref. [39].



And a step towards realizing  
That *potentially* there is...

